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A decade of astrocombs: recent advances in frequency combs for astronomy

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Abstract: A new regime of precision radial-velocity measurements in the search for Earth-like exoplanets is being facilitated by high-resolution spectrographs calibrated by laser frequency combs. Here we review recent advances in the development of astrocomb technology, and discuss the state of the field going forward.

OCIS codes: (120.6200) Spectrometers and spectroscopic instrumentation; (350.1260) Astronomical optics.

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1. Introduction

High resolution spectroscopy underpins most fields of astrophysics and has enabled major progress in multiple areas, such as the initial discovery of a planet orbiting a solar-type star [1] which led to the characterization of an exoplanet atmosphere [2], the study of metal-poor stars [3], as well as the chemical evolution of the Galactic bulge [4]. With suitably well-calibrated instruments, astronomical spectroscopy will explore some of the most fundamental concepts in physics and cosmology, including the search for dark energy and observing the expansion of the universe in real time [5].

A new generation of precision spectrographs (such as CARMENES, ESPRESSO and HIRES) is needed for experiments planned for the European Extremely Large Telescope (E-ELT), Very Large Telescope (VLT) and other projects. These experiments need to detect a radial velocity Doppler shift with a precision as high as 2 cm s^{-1} [6], implying the need for an extremely stable wavelength reference for spectrograph calibration. Current spectrographs are limited by the irregular line spacings, drifts and aging of the Th-Ar lamps [7] and I_2 cells [8] which are conventionally used, motivating the adoption of laser frequency combs as the preferred calibration sources for future instruments [9].

Frequency combs provide the precision needed by future high-resolution spectrographs in the form of a broadband, exactly-calibrated spectral 'ruler', whose accuracy is traceable to the SI second via a GPS radio-frequency reference. The uniformly-spaced, bright, and narrow features of the comb spectrum are ideal for optical frequency calibration, while the absolute traceability of the comb allows for comparisons of observations made on timescales from days to years, even at different observatories. A frequency comb can serve as both a perpetual calibrator, either solo or in tandem with a hollow cathode lamp, and as an identifier of systematic errors in the spectrograph, such as pixel mask stitching defects [10].

The potential for such 'astrocombs' to have a major impact on the astronomy community has been widely heralded [11], however multiple technical challenges stem from the conflicting requirements of providing comb-line spacings in the 5-50 GHz range across a wavelength bandwidth from 380 nm (Ca II H and K lines) to 2.4 μm (CO band at 2.3 μm), as high-peak-power pulses are typically only available at low pulse repetition frequencies.

The remainder of this article develops the core concepts underpinning astrocombs, starting from an understanding of the technical requirements of an astrocomb as a wavelength calibrator. We review the development of astrocomb systems, which can now be divided into fiber, solid-state and electro-optic comb approaches, which are each characterized by a distinct set of performance features and technological approaches. These comb configurations are explained in detail, allowing their relative performance to be critically compared. Finally, we discuss the state of the field going forward, examining the opportunities and challenges that lie ahead for the astrocomb community.

2. Astrocombs

A laser frequency comb provides a large number of narrow, equally spaced optical modes, the frequencies of which are given by $f_n = nf_{REP} + f_{CEO}$, where n is a large integer, f_{REP} is the mode spacing and f_{CEO} is an offset from a frequency grid that would pass through zero [12]. Stabilization of both f_{REP} and f_{CEO} is carried out to provide a set of comb lines whose frequencies are well known and are traceable to primary standards. In this section we detail the technical requirements of an astrocomb, such as mode spacing, spectral coverage and frequency precision. We then describe common methods for creating astrocombs and review related technologies.

2.1 Concept

Astrocombs must fulfill a number of criteria for use as spectrograph calibrators. Aside from matching the wavelength coverage of the spectrograph itself, the comb spacing must be tailored to match the spectrograph resolving power $R = \lambda/\Delta\lambda$. Each comb tooth should be individually unresolved, yet adjacent comb modes must be resolved from one another. As a frequency comb is essentially a series of delta functions, the former requirement is easily fulfilled, and enables the comb to interrogate the instrument response. The latter requirement provides a series of frequency markers on the spectrograph CCD, with the frequency spacing selected to optimize the number of lines per resolution element [11]. With accurate centroiding of the comb lines on the CCD, a precise wavelength solution for the spectrograph can be constructed.

The two primary challenges facing practical astrocomb development are (i) achieving the required spectral coverage and (ii) matching the comb mode spacing to the spectrograph resolving power. Coverage can be addressed by combining the choice of laser gain medium with spectral broadening in suitable fiber or other well-established nonlinear techniques. The resolving power of a high-resolution spectrograph is typically >10,000, with corresponding optimal mode spacing >10 GHz, with the exact choice being wavelength dependent. This repetition frequency is not readily obtainable from typical femtosecond laser systems, and the most widely-adopted solution has been to optically filter the modes of a lower repetition frequency laser ($f_{REP} \leq 1$ GHz) in a Fabry-Pérot etalon, as discussed in §2.3.1 and shown in Fig. 1.

Figure 2 illustrates six system architectures (A-F) that have been employed in astrocombs. The simplest architecture (A) is to directly filter the output of the source comb to achieve the required mode spacing. This approach is intrinsically narrowband, restricting the range over which a spectrograph can be calibrated. Two simple extensions of this approach are to frequency double (B) or spectrally broaden (C) the laser output before filtering to extend the astrocomb coverage. Architectures (D) and (E) are commonly employed by fiber-based astrocombs, where low power, low-repetition-rate oscillators require significant filtering to remove unwanted modes, as well as amplification to achieve sufficient peak power for nonlinear frequency conversion processes. The approach illustrated in (F) is used in electro-optically modulated combs and is described in §2.2.3.

2.2 Astrocomb laser technologies

The photonics community has driven the majority of astrocomb development, and as a result a number of competing approaches have been advanced in parallel, separated by their different choices of laser technology. Below we discuss progress in the development of high repetition rate fiber and solid-state lasers, limiting the scope to systems that can be stabilized into frequency combs. We also describe alternative laser comb technologies such as electro-optically modulated CW lasers and microresonators.

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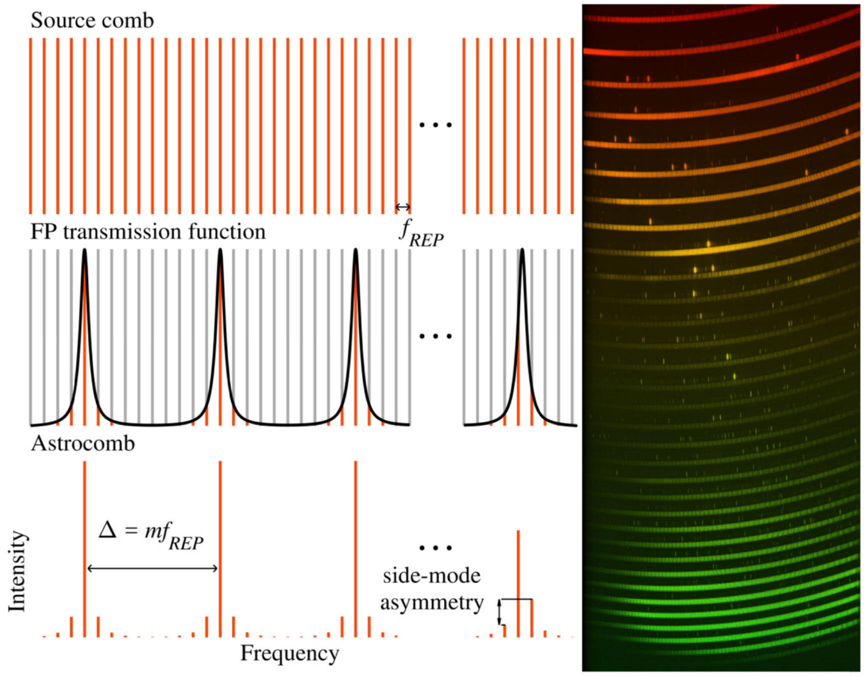

Fig. 1. Left: the dense modes of a low-repetition-rate frequency comb can be filtered in a Fabry-Pérot etalon to provide a wider mode spacing. If the group delay dispersion of the etalon is not zero then unwanted modes can be insufficiently or asymmetrically suppressed (exaggerated for effect). Right: a false-color CCD image of the 15-GHz astrocomb deployed at the Southern African Large Telescope [13].

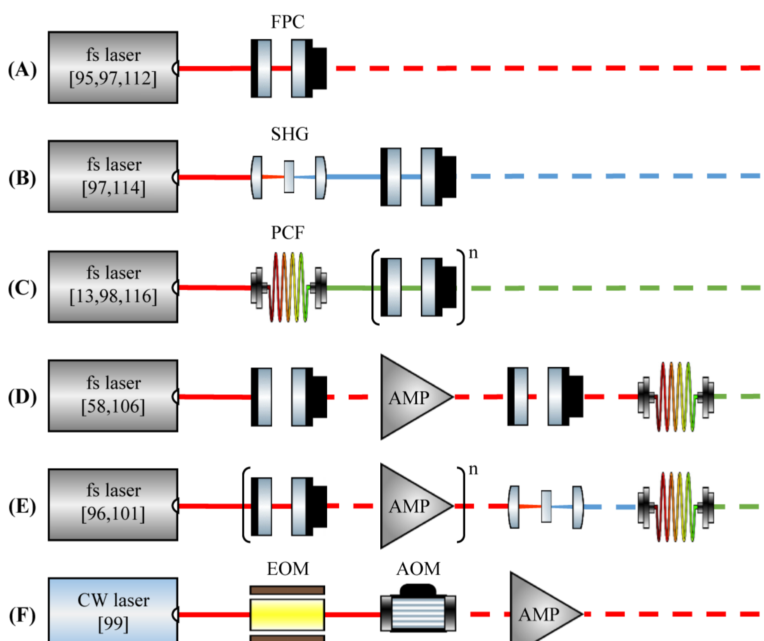

Fig. 2. Illustration of different astrocomb architectures. FPC, Fabry-Pérot cavity; SHG, second harmonic generation; PCF, photonic crystal fiber; AMP, amplifier; EOM; electro-optic modulator; AOM, acousto-optic modulator. See text in §2.1 for further details.

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2.2.1 Fiber combs

Fiber laser frequency combs have proven to be compact and robust [14], with hands-free operation and little warm-up time. Erbium and ytterbium fiber lasers typically produce ~100 mW of average power which can be readily amplified to upwards of 10 W, with sub-ps compressed pulse durations. While the long-term stability and turnkey operation offered by fiber combs is highly desirable for telescope support staff or operators of non-robotic telescopes (who have little or no laser training), these systems still face significant technical challenges when used as the source laser for an astrocomb. The relatively narrow native spectral coverage of fiber systems requires broadening or wavelength shifting in order to match the operating region of many spectrographs. Commercially available fiber laser repetition rates are often limited to 250 MHz [15], particularly in all-fiber designs, and so the comb modes must be significantly filtered to achieve the >10 GHz mode spacing for spectrograph calibration. Both of these processes require amplification, however this can introduce unwanted side-effects such as third-order dispersion or sideband amplification due to four-wave mixing, and can also lead to component damage, particularly in the amplifier pump diodes and fibers.

Wider mode spacing fiber lasers have been developed using a variety of novel techniques. A 1.04-GHz Yb:fiber laser with a high doping level (up to 6 wt. %) produced 100 mW average power that was amplified in cladding-pumped fiber and compressed in order to produce an octave-spanning supercontinuum in suspended core fiber. This marked the first demonstration of a GHz fiber comb without mode filtering [16], however repetition rate scaling was limited by the use of bulky free-space dispersion compensation and the length of the gain fiber. A solution was found by employing a Yb-doped phosphate glass fiber with 15.2 wt. % for increased gain along with a dispersion compensating output coupler, producing 200 fs pulses at 3 GHz repetition rate [17]. Shorter pulses were achieved at 1 GHz using nonlinear-polarization-rotation mode-locking, which also provided higher output power for octave-spanning supercontinuum generation without prior amplification [18]. Recently a fully-stabilized 750-MHz Yb:fiber comb was reported which achieved f-to-2f self-referencing without external amplification [19].

By using a saturable-absorber-mode-locked Er:fiber laser GHz repetition rates have also been also been demonstrated [20], with comb stabilization carried out using highly-nonlinear fiber (HNLF) for supercontinuum generation and an acousto-optic frequency shifter for f_{CEO} stabilization using the feed-forward technique [21]. An alternative approach uses the passive mode-locking of all-fiber Fabry-Pérot lasers by graphene or carbon-nanotube saturable absorbers to achieve multi-GHz repetition rates. These lasers use short lengths of Er:Yb phosphosilicate fiber, enabling compact footprints with low losses at the expense of increased pulse durations [22,23].

2.2.2 Solid-state combs

While fiber laser combs are compact and stable, solid-state systems offer shorter pulses and higher average powers directly from the oscillator, removing the need for external amplification stages. Moreover, GHz-repetition-rate Ti:sapphire lasers are now commercially available. Such higher repetition rates reduce the demands of the Fabry-Pérot filtering stages while still supplying sufficient pulse energies for coherent spectral broadening [24] or other nonlinear techniques [25]. Technical challenges facing these systems in an astrocomb include less-developed automation, noise factors associated with the free-space architecture, and long-term performance drift due to unwanted contaminants.

Ti:sapphire lasers exploit their large gain bandwidth and employ Kerr-lens mode-locking to routinely provide sub-40-fs pulses at GHz repetition rates. An octave-spanning 1-GHz Ti:sapphire laser enabled comb stabilization without additional spectral broadening [26], while 2-GHz and 5-GHz ring cavities have employed photonic crystal fiber (PCF) to achieve the same coverage [27,28]. The highest repetition rate reported so far has been 10 GHz [29], and self-referencing was achieved with only 120 pJ pulse energy by coupling 560 mW of average power through a 2-m-long micro-structured fiber with a 1.5-µm core and zero-dispersion wavelength near 590 nm [30]. Diode-pumped Cr-doped lasers can operate at Ti:sapphire and Er:fiber wavelengths, providing femtosecond pulses at high repetition rates. A 1-GHz Cr:LiSAF laser producing 55-fs pulses at 863 nm was reported [31], which could potentially be broadened in standard PCF. A three-element Cr^{4+}:YAG laser with a 4-GHz repetition rate was developed for terabit communications, producing 82-fs pulses at 1525 nm [32].

Yb-doped gain media can be pumped by affordable and highly efficient laser diodes and can be subsequently amplified in Yb:fiber, making them excellent candidates for compact comb systems. The first passively mode-locked high repetition rate Yb:KYW laser was a 4-mirror ring cavity producing 1-GHz pulses [33]. A more compact and efficient design employed a semiconductor saturable absorber mirror (SESAM) for mode-locking [34], which also enabled the repetition rate to be extended to 2.8 GHz [35]. Recent efforts have exploited the high thermal conductivity and nonlinear refractive index of Yb:KYW to demonstrate a 4.6-GHz Kerr-lens mode-locked laser [36], which provides a broader spectrum and shorter pulses than SESAM mode-locking. Yb:ceramic lasers possess similar properties, and have been used to demonstrate repetition rates up to 15-GHz [37,38].

SESAM mode-locked Yb:KGW lasers have been developed extensively since 2010, when a 1-GHz laser producing 281-fs pulses with 1.1 W average power was reported [39]. This laser was subsequently broadened in PCF and f_{CEO} detected in an f-to-$2f$ interferometer [40], however despite a strong signal-to-noise level [41] locking was not achieved due to complexities in stabilizing the offset frequency using pump diode current modulation [42]. The highest repetition rate Yb:KGW laser reported thus far is 4.8 GHz [43], however the corresponding decrease in intracavity pulse energy resulted in insufficient self-phase modulation for coherent supercontinuum generation, with output pulse durations of 400 fs. Yb:CALGO (Yb:$CaGdAlO_4$) is a promising gain medium for the generation of sub-100fs pulses due to its low material dispersion (~100 fs^2/mm) and broad absorption and emission cross sections. A 1.8-GHz Yb:CALGO laser producing 60-fs pulses with 2.95 W average power was reported [44], and comb stabilization achieved without additional amplification or pulse compression [45]. This work has been extended to 5 GHz [46] and 10 GHz [47], however comb stabilization has not been attempted.

Higher repetition rates (10 – 160 GHz) are achievable in Nd:YVO_4 and Er:Yb:glass by combining compact cavity designs with suitable SESAMs [48,49], however pulse durations increase correspondingly to >1 ps, making coherent spectral broadening unfeasible. Semiconductor disk lasers such as VECSELs and MIXSELs offer wide mode spacings, but self-referencing has only been observed in limited circumstances [50].

2.2.3 Electro-optically modulated combs

In contrast to the laser systems described above, electro-optically modulated (EOM) frequency combs take an alternative approach to achieving the required optimal mode spacing, negating the use of Fabry-Pérot etalons at the expense of long-term stability [51] and increased modal position uncertainty. For self-referenced combs the positional uncertainty contains contributions from the microwave references used to stabilize f_{CEO} and f_{REP}, with the former frequency requiring an additional measurement to remove an aliasing ambiguity and the uncertainty in f_{REP} being the dominant factor when scaled up by n to the optical domain. In an EOM comb a narrow-line CW pump laser is phase modulated to produce sidebands with a spacing set by the modulation frequency. Absolute traceability is achieved by stabilizing the pump laser to an atomic reference (also preventing wavelength shifts) and through microwave referencing of the modulation frequency, and thus the dominant uncertainty becomes the precision to which the CW laser can be stabilized to $f_{atom} = f_{CEO}$. With commercial modulators primarily available at telecommunications wavelengths, EOM

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combs have been limited to the 1-2 μm band, and octave-spanning coverage has only been demonstrated in a few instances [52].

2.2.4 Chip-scale frequency combs

Microresonators are chip-scale devices that exploit the nonlinear Kerr effect in a dielectric medium to produce multi-GHz line spacings without filtering [53]. While the promise of robust, compact and stable chip-scale frequency combs is appealing, this technology is still in an early developmental stage, with much work required to improve device repeatability, modal noise and spectral coverage. The development of microresonators has primary used silica or a crystalline material such as CaF_2 as a gain medium, with spectral output centered in the infrared. Recent work has enabled coherent *f*-to-2*f* self-referencing of a 16.4 GHz microresonator comb via external broadening [54]. In the future this broadening could be achieved with chip-integrated highly nonlinear waveguides [55], with filtering and delay functions integrated onto the supercontinuum chip to create a compact visible frequency comb.

2.3 Ancillary astrocomb technologies

Aside from the master laser oscillator, an astrocomb typically contains one or more of the following ancillary components in order to produce the desired spectral coverage and mode spacing for spectrograph calibration.

2.3.1 Fabry-Perot etalons

The dense mode spacing of the typical frequency combs produced directly by mode-locked lasers (≤1 GHz) requires spectral filtering of >90% of the modes with one or more Fabry-Pérot etalons to produce a calibration grid matched to the resolving power of the spectrograph. A Fabry-Pérot etalon spectrally selects a set of modes from the input comb with frequency spacing f_{REP}, with the length of the cavity selected such that the free spectral range (FSR) of the etalon passes every *m*th comb mode, creating an output comb with frequency spacing mf_{REP} [56]. While simple in theory, in practice this approach is complicated by the broad bandwidths required for spectrograph calibration. Additional factors must be taken into account, including air dispersion inside the etalon, the phase contribution of the mirror coatings, and the Gouy phase shift [57]. The spectral transmission function of a Fabry-Pérot etalon consisting of two mirrors with reflectivity R separated by distance L is given by:

$$T\left(f, R, L(\lambda)\right) = \frac{(1-R)^2}{(1-R)^2 + 4R\sin^2\left(2\pi fL(\lambda)/c\right)} \tag{1}$$

The dispersion of the etalon is included in the term $L(\lambda)$, and leads to a misalignment between the regular grid of comb modes and the FSR of the etalon. For demanding applications such as filtering the modes of a 250 MHz fiber laser to 25 GHz [58], the filter ratio of $m = 100$ would require a reflectivity of $R = 99.8\%$, extremely difficult to obtain over a broad bandwidth without introducing additional mirror dispersion. A solution is to use cascaded etalons, relaxing the reflectivity requirements on each individual cavity and increasing the operating bandwidth, with care taken to prevent the introduction of virtual cavities arising from spurious back reflections. Sideband suppression of 70 dB has been reported using this technique with a double etalon [59]. For extremely broadband applications the lower reflectivity of metallic coatings (<99%) can be combined with multiple filter stages to provide almost dispersion-free etalons. Advances in dielectric coating design and manufacturing have led to the production of mirror sets with highly tailored group delay dispersion (GDD), primarily for femtosecond laser applications [60]. Recently mirror pairs with complementary coatings designed to provide zero GDD have been reported [61]. When combined with the dispersion of air, these mirror sets provide high fidelity filtering without FSR misalignment [62].

Inadequate filtering of the fundamental comb leads to poor suppression of unwanted modes, as well as intensity asymmetry between sidebands on either side of the transmitted mode. These sidebands cause a shift δf_m in the center of mass of an astrocomb line f_m as measured on the spectrograph, given by [63]:

$$\delta f_m \approx f_{REP}\left(\frac{\Delta_m / f_{REP}}{2F}\right)^2\left[\frac{t_{m+1}I_{m+1}-t_{m-1}I_{m-1}}{t_m I_m}-2\frac{\delta\phi_m}{\pi}\frac{\Delta_m}{f_{REP}}\right] \tag{2}$$

where F is the etalon finesse, Φ_m is the round trip phase delay, I_m is the source comb line intensity and t_m is the resonant transmission of the Fabry-Pérot etalon at f_m. Analysis of this model has shown that centroid shifts of 7 cm s^{-1} can occur when neighboring comb lines differ by as little as 1%. Such systematic errors must be measured and corrected for when striving to achieve calibration accuracy at the 1 cm s^{-1} level. An in-depth analysis of the effects of sideband suppression and asymmetry indicated that long-term radial velocity accuracy is limited by drifts in the alignment of the Fabry-Pérot etalon [64].

2.3.2 Nonlinear frequency conversion

As shown by the dashed lines in Fig. 3, the spectral coverage of a high-resolution spectrograph is often extremely wide, making external frequency conversion of the source comb a necessity. The most common approach is to use PCF to generate a broadband supercontinuum [65], exploiting the high average powers or short pulses available to fiber and Ti:sapphire lasers respectively. Care must be taken to maintain phase coherence, otherwise there will be a shift in the position of the comb modes in the wings of the supercontinuum. In cases where pulse energies are low, tapered fibers can be employed to increase the nonlinear broadening effects [66].

Second harmonic generation enables access to green and blue wavelength regions that would otherwise be inaccessible using conventional PCF. Engineered grating periods in quasi-phase-matched crystals such as PPLN or PPKTP can produce top-hat spectra with increased phase-matching bandwidths compared to birefringent crystals such as BBO or LBO [67]. The tailoring of spectral profiles could be used to remove or relax the need for subsequent active spectral flattening, as described in §2.3.3.

Frequency down-conversion through parametric processes can be used to extend a comb to the near- and mid-infrared, however care must be taken to keep track of the comb offset frequency. Difference frequency generation (DFG) can produce offset-free combs [68], useful as they remove an ambiguity in the absolute frequency of each comb mode, however few spectrographs operate in the regions typically accessed through DFG. Optical parametric oscillator (OPO) frequency combs are as intrinsically stable as their pump [69], however the signal and idler offset frequencies are distinct from that of the pump laser [70]. Degenerate OPOs produce extremely broadband outputs at twice the pump wavelength, with a comb that is intrinsically locked to that of the pump laser [71]. Such systems are currently proposed in the calibration system for the planned HIRES spectrograph on the E-ELT [72].

Effective sideband suppression can be made more difficult by the use of nonlinear conversion techniques, particularly when using amplifiers in a fiber-based astrocomb. Chang *et al.* [73] studied a number of configurations of filtering schemes and amplifiers, and determined that the nonlinear phase introduced during chirped-pulse amplification reintroduces previously suppressed side modes, with two filter stages required prior to amplification to minimize this effect. The same team also studied the effects of nonlinear spectral broadening on filtered comb modes [74], noting that four-wave-mixing processes between astrocomb lines and side modes degraded the sideband suppression. Again, using multiple filter cavities prior to broadening was shown to alleviate this issue. In separate work,

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Probst *et al.* [75] analyzed the effects of sideband amplification in PCF in SHG processes, drawing similar conclusions. While it may seem evident that broadening prior to filtering would remove this issue, it is worth noting that filtering is made relatively simpler when it is carried out at the pump wavelength due to the narrower spectral coverage and relaxed requirements of the mirror coatings.

2.3.3 Spectral flattening

As well as line spacing uniformity, an ideal calibrator provides a constant flux of photons per comb line to the CCD to maximize the signal-to-noise ratio in a given exposure time for the highest possible precision, and therefore the uniformity of the spectral intensity of the astrocomb must be considered. Most nonlinear broadening processes result in a highly-modulated envelope due to Raman soliton and four-wave mixing processes. Spectral shaping [76] of a lab-based astrocomb has been demonstrated using a spatial light modulator placed at the image plane of a grating spectrometer and between a pair of crossed polarizers, with a CCD spectrometer used in an adaptive feedback loop [77,78], and a spectral flattening module was added to the HARPS astrocomb in a recent upgrade [79] (see §3.1). Further work is required to extend this flattening process to the infrared.

2.3.4 Absolute comb mode identification and traceability

For precision calibration it is necessary to identify the absolute frequency of each comb tooth, requiring knowledge of the mode number as well as f_{REP} and f_{CEO}. Two ambiguities in this identification process exist and must be addressed. The first is in the determination of the offset frequency, as standard f-to-$2f$ interferometry techniques are unable to distinguish between f_{CEO} and f_{REP}-f_{CEO} without an additional measurement, typically beating a stabilized CW laser with a comb line then fractionally shifting f_{REP} to observe how this beat frequency shifts. The second ambiguity arises in determining which subset of modes has been filtered by the Fabry-Pérot etalon, as the filtering process can transmit any subset that falls within the free spectral range of the mirrors.

A common approach to address this issue has been to use a narrow linewidth CW laser as a reference frequency. If the CW laser is locked to the comb then a wavemeter must be used to determine the absolute frequency of one comb tooth, from which the remaining comb teeth can be calculated [80]. The frequency stability of a wavemeter is not suitable for long-term precision measurements of a single comb line [81], however it does allow the modal number ambiguity to be resolved. Alternatively, the CW laser can be stabilized to an atomic transition to provide absolute traceability, and the comb offset frequency stabilized relative to this reference [82]. The offset frequency ambiguity can be resolved by shifting f_{REP} by a known value and observing the shift in f_{CW}-f_n. In either case the CW reference can also be used to stabilize the Fabry-Pérot etalon spacing using the Pound-Drever-Hall method, ensuring that transmitting the CW laser also transmits a known subset of modes.

The above method is well suited for narrow bandwidth astrocombs that employ filter cavities operating over a single spectral region, however future spectrographs such as E-ELT-HIRES require astrocombs which can provide a calibration scale extending over nearly three octaves of optical frequency [72,83]. The design approach taken in such spectrographs is to divide the light into discrete wavelength channels (up to eight in E-ELT-HIRES) from the UV to the mid-IR, implying a requirement not only for a broadband astrocomb but also for multiple Fabry-Pérot etalons, each filtering the astrocomb within a unique wavelength region. Narrow-line and atomically referenceable CW lasers are not generally available across such a wide spectral range, with most diode lasers used for atomic spectroscopy operating in the UV-visible region [84,85]. We recently proposed an alternative technique in which the Fabry-Pérot cavity is locked directly to the comb and a Fourier-transform spectrometer (FTS) with resolution sufficient to resolve the filtered comb is employed as a mode identifier [86]. Calibrating the scanned optical path length of the FTS with a single atomically-stabilized

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diode laser ensures traceability, and an all-metallic design enables broadband operation. Combined with retrieval techniques that can surpass the path-limiting resolution of conventional FTS [87,88], the absolute comb frequencies could be identified without the need for additional CW lasers or a wavemeter.

For absolute traceability to SI standards the RF synthesizers used to stabilize f_{REP} and f_{CEO} can be referenced to GPS disciplined microwave clocks. These clocks are the primary source of uncertainty in the comb mode positions, as small fluctuations in f_{REP} in the RF domain are multiplied by the mode number n, creating larger errors in the optical domain. Long-term averaging can reduce the uncertainty to below the 10^{-12} level, with the one-day frequency stability of almost all the satellite clocks forming the GPS constellation being reported as $< 2 \times 10^{-13}$ [89]. Referencing and archiving of GPS timing signals against a terrestrial master clock operated by the US Department of Defense ensures long-term traceability of these data can limit their daily drift to $< 2 \times 10^{-14}$ [89]. This long-term precision, which is ultimately determined by the terrestrial primary Cs standard, is important for several ambitious science cases which require consistent comb performance over many observations, such as measuring the radial velocity variations over the long orbital period of an Earth-like exoplanet, testing the postulated variation with redshift and direction on the sky of the fundamental fine structure constant α [90], and directly measuring the dynamical evolution of the Universe over time (the Sandage test) [91]. Observational campaigns conducted on a single instrument are likely to be precision limited, but in cases where observations from more than one telescope might be combined then the question of absolute calibration accuracy also becomes important and would be subject to the same limitations imposed by GPS referencing.

3. Review of demonstrated astrocombs

In this section we review the systems that have been deployed or identified as potential astrocombs. Where possible, we present work chronologically by research group, reflecting advances in the field, and separating the discussion by laser system. Figure 3 illustrates the wavelength coverage of several spectrographs and the astrocombs that have been deployed to calibrate them, with further detail provided in Table 1 and the text below. Note that the spectral gap from 900 to 1400 nm in Fig. 3 does not reflect a lack of suitable comb sources, but is due to a combination of other factors including increased atmospheric water vapor absorption [97], a decrease in detector performance for instruments typically designed for operation in the visible or IR, and a lack of science justification for high detail observations in this region, although this will change with the advent of instruments such as CARMENES [98] and NIRPS [99].

3.1 Fiber lasers

Researchers working in collaboration with Menlo Systems have utilized fiber combs to calibrate multiple spectrographs. The initial field demonstration of an astrocomb was carried out in 2008 on the solar spectrograph at the Vacuum Tower Telescope (VTT) at Tenerife, Canary Islands [92]. A Fabry-Pérot etalon with <40-nm bandwidth at 1570 nm filtered the modes of a 250 MHz Er:fiber comb to 15 GHz, with >30-dB sideband suppression. The etalon was dither-locked to a transmission maximum, with mode number identification carried out by locking a CW laser to a comb line and measuring this frequency with a wavemeter. As the VTT spectrograph is not stabilized, drifts of 8 m s^{-1} min^{-1} were clearly evident using the comb, which were not observable with thorium lamp calibration.

After this initial promising demonstration, the Menlo Systems comb was installed as the calibrator for the High Accuracy Radial velocity Planet Searcher (HARPS) spectrograph at European Southern Observatory's 3.6-m telescope at La Silla, Chile [10]. HARPS has a resolving power of R = 115000 and covers the 380-690 nm range, with a long term precision of 1 m s^{-1}. The HARPS comb consisted of a 250-MHz Yb:fiber laser filtered to 18 GHz in two Fabry-Pérot etalons with different FSRs, providing >50-dB sideband suppression. The cavities were tilt-locked to a CW laser, itself locked to the comb and frequency monitored with a wavemeter, enabling the same subset of modes to be transmitted by both etalons. Amplifiers were employed before, between, and after the etalons to provide adequate power for frequency doubling to 515 nm, with sufficient bandwidth to cover a single spectral order. The uncertainty in the comb line positions was 2.1 cm s^{-1} after subtracting instrument drift. Analysis of the residuals in the calibration curve revealed detector inhomogeneities every 512 pixels, deriving from the mask used in the manufacturing process.

Table 1. Summary of astrocombs implemented at an on-site spectrograph

Spectrograph	VTT [92]	VTT [93]	HARPS/ FOCES [79]	Pathfinder [58]	TRES [94]	HARPS-N [95]	HRS [13]	NIRSPEC [96]
Comb source	Er:fiber	Yb:fiber	Yb:fiber	Er:fiber	Ti:sapphire	Ti:sapphire	Ti:sapphire	EOM
Source f_{REP} (GHz)	0.25	0.25	0.25	0.25	1	1	1	CW
Astrocomb f_{REP} (GHz)	15	5.5	18 / 25	25	30/50	16	15/25	12
Bandwidth (nm)	1530-1600	480-640	440-600	1450-1700	400-420 / 780-880	500-620	555-890	1430-1640
No. Fabry-Perot etalons	1	2	3	2	1	2	1	N/A
Fabry-Perot finesse	2400	3000	2600	2000	250	105	155	N/A
Sidemode suppression (dB)	46	94	55	50	22	45	20	N/A
No. amplification stages	0	3	3	2	0	0	0	2

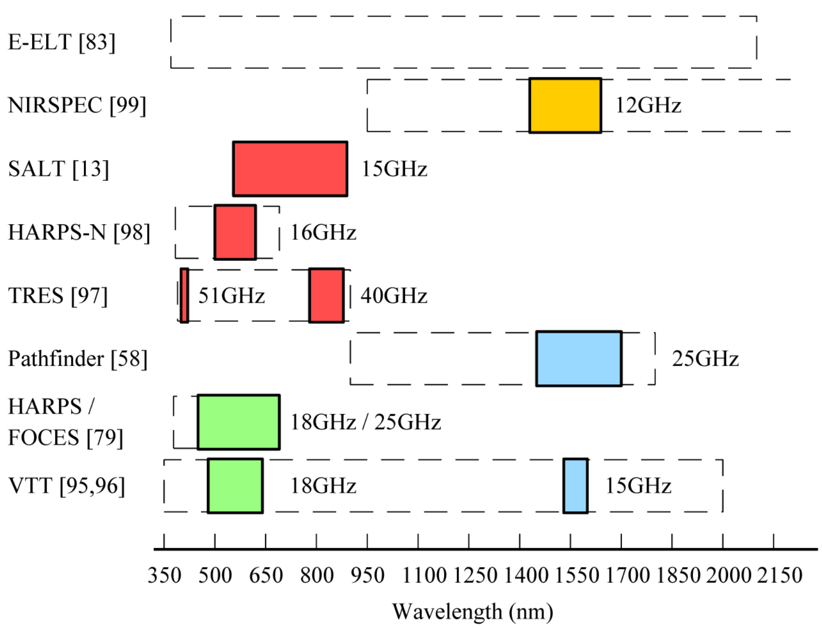

Fig. 3. Comparison of the astrocomb calibration campaigns on astronomical spectrographs. Colored boxes show the achieved spectral coverage of the astrocomb, with colours indicating the employed laser technology, where blue is Er:fibre, green is Yb:fibre, red is Ti:sapphire and orange is an EOM comb. Dashed lines indicate the entire spectral coverage of the spectrograph. The coverage of NIRSPEC extends to 5500 nm.

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To calibrate further spectral orders the frequency-doubled filtered comb was broadened in tapered PCF with a core diameter <1 μm [100]. With 90-mW input pulses at 18 GHz (5 pJ pulse energy), the output spectrum was 140 nm wide at 20 dB below the peak [101]. This astrocomb was used to calibrate the radial velocity shifts of the star HD 75289, orbited by a Jupiter-mass exoplanet with a period of 3.5 days. The orbit of the planet was reconstructed with the same uncertainty as previous measurements using a Thorium lamp, suggesting that additional factors were limiting the calibration. The HARPS comb was also used to calibrate a solar atlas using sunlight reflected from the surface of the moon, in which CCD stitching errors revealed previously were measured for multiple spectral orders [102].

A similar Yb:fiber comb was installed on the VTT telescope in 2011. Filtering of the pump laser was carried out using a pair of identical Fabry-Pérot etalons locked with the Pound-Drever-Hall method to the transmission of an orthogonally-polarized CW laser stabilized to a comb mode [103]. The etalon finesse was increased to ~3000, with sideband suppression >94dB. Simultaneous coupling of sunlight and calibration light into the same single mode fiber removed systematic effects related to grating illumination. Results identified a number of systematic errors in the calibration, including camera vibrations from a cooling fan, imperfections in the microlens array, and variations in the point-spread function arising from changes in the fiber coupling [93].

A Menlo Systems astrocomb was used to determine the calibration precision and stability of the upgraded Fiber Optic Cassegrain Échelle Spectrograph (FOCES), previously installed at the Calar Alto 2.2m telescope and current housed at the Wendelstein Observatory, Germany. The astrocomb architecture is similar to those described above but with 25-GHz mode spacing, and spectral broadening achieved directly in tapered fiber rather than after an intermediate frequency-doubling stage [104]. An identical astrocomb has been installed at the Xinglong station of the National Astronomical Observatory of China [105], however further results have not yet been reported. The HARPS astrocomb was upgraded to a similar architecture in 2015 while maintaining a 18-GHz mode spacing, and the FOCES astrocomb transported to La Silla in order to compare the relative stability of these two calibration sources [79]. An additional temporally incoherent spectral background was observed in the new HARPS comb that was not previously present, and was attributed to amplified spontaneous emission (ASE) produced in the power amplification stage. The calibration repeatability of 1 cm s^{-1} was attainable on a time scale of a few hours, with other systematics in the spectrograph such as multimode fiber noise and spectrograph channel cross-talk currently preventing longer-term calibration.

Researchers at NIST generated a 12.5-GHz comb by filtering a 250-MHz Er:fiber laser in a pair of high finesse (F = 2000) etalons that were dither locked to a peak of transmitted power [106]. The etalons were constructed from curved rather than planar mirrors, with the curvature selected to offset higher order spatial modes by + 1.75 GHz from the main 12.5-GHz spaced modes. Intermediate amplification after the first etalon with a pair of semiconductor optical amplifiers preserved the spectral bandwidth before launching into a high power EDFA and subsequently into the second etalon. The filtered pulse train was broadened in 50 m of HNLF. The sideband suppression was measured by optically heterodyning the 12.5-GHz comb with a tunable CW laser. While asymmetry was noted after amplification, it was not detected after broadening. The frequency accuracy of this comb was evaluated throughout the optical chain by referencing a single mode to a 10-MHz hydrogen-maser reference. At each stage the optical mode fluctuations tracked the GPS disciplined oscillator used for f_{REP} locking, suggesting that this was the limiting factor. In separate work [58], this laser was further filtered to 25 GHz with 50dB sideband suppression and used to calibrate the Pathfinder spectrograph on the Hobby-Eberly telescope in Texas with a radial velocity precision of 10 m s^{-1}. This is currently being extended to 30 GHz in the near infrared through the use of three low dispersion etalons [107]. Complementary work in Yb:fiber has been carried out by Hou *et al.* [108], generating a 23.75-GHz comb with 43dB sideband suppression.

An astrocomb is being developed for the infrared (0.9-2.5 μm) GIANO spectrograph located on the Telescopio Nazionale Galileo (TNG) in La Palma, Spain [109]. A 100-MHz Er:fiber laser will be filtered to 16 GHz in two moderate finesse etalons (F = 600) before amplification and broadening in HNLF. Alternatively, should sideband suppression be insufficient, the etalons will be composed of metallic mirrors to minimize dispersion, allowing broadening to be undertaken at 100 MHz with no amplification but requiring additional etalon stages.

Murphy *et al.* [110] demonstrated the measurement of both the instrument line shape and inter-pixel sensitivity variation on the Ultra-High-Resolution Facility (UHRF) spectrograph at the Anglo-Australian Telescope (ATT), Australia. With $R \approx 10^6$, a mode spacing of 1 GHz was sufficient to resolve the comb lines. A 94-MHz Er:fiber laser was stabilized to the 100th harmonic of f_{REP} and the offset frequency was monitored using the $2f$-to-$3f$ technique.

Ma *et al.* [111] have developed an astrocomb based on a 1-GHz Yb:fiber laser with sufficient bandwidth and output power for comb stabilization [18]. The laser output was amplified to 2.8 W in 4.5 m of double-cladding Yb:fiber and compressed to < 100 fs using a grating pair in order to generate a supercontinuum in a tapered PCF. A Zerodur-spaced Fabry-Pérot etalon composed of a complementary pair of zero-GDD mirrors [61] for transmission over 430–700 nm with 26 dB sideband suppression. Initial tests at the Xinglong station of the National Astronomical Observatory of China show an estimated RV resolution of 29 cm s^{-1}, but with asymmetric filtered comb lines due to etalon phase errors.

3.2 Ti:sapphire lasers

The first laboratory demonstration of an astrocomb was carried out in 2008 by Li *et al.* [112] by employing an octave-spanning Ti:sapphire laser with 1-GHz mode spacing [113], enabling direct stabilization of f_{CEO} without further spectral broadening. A Fabry-Pérot etalon locked to a Rb-stabilized diode laser provided up to 40-GHz mode spacing in the range of 770-920 nm. This work was extended to the visible by frequency doubling the Ti:sapphire output in a 1-mm-thick BBO crystal, proving more robust and reliable than broadening in PCF. The comb was installed on the TRES spectrograph at the Fred Laurence Whipple Observatory (FLWO) on Mt. Hopkins, Arizona. A Fabry-Pérot etalon operating over 400–420 nm provided a mode spacing of 51 GHz with 20-dB sideband suppression [114]. Both the near-infrared and blue astrocombs were used to calibrate TRES, indicating that 1-m s^{-1} resolution should be achievable once temperature, pressure and vibration controls are installed [94,115].

The same research group designed and installed an astrocomb at HARPS-N, located on the TNG in the Canary Islands [116]. In contrast to the heavily filtered and amplified Yb:fiber comb used to calibrate HARPS, the 1-GHz Ti:sapphire employed in this system requires less demanding mode filtering in order to achieve the optimal spacing, however tapered PCF was still required to satisfy the spectral coverage demands of the spectrograph. An 11-mm length of solid core PCF (NKT PM850) was adiabatically tapered from an initial core size of 3 μm to 1.7 μm, generating an output from 500 to 620 nm through fiber optic Cherenkov radiation [117]. The green comb modes were filtered to 16 GHz in an etalon stabilized with a low noise frequency doubled Nd:YAG laser, using the Pound-Drever-Hall method and a high-bandwidth piezo for cavity length feedback. The entire Fabry-Pérot system was isolated from DC to 2 kHz, and the temperature held at 5 K above ambient to better than 100 mK. Tests showed that the system was capable of sub-10-cm s^{-1} stability over long time scales [95]. This comb was also used in a series of experiments to observe the Sun as a star, measuring sub-m s^{-1} Earth-Sun RV shifts [118]. Ongoing work will attempt to extract the signature of Venus from the measured RV profile, demonstrating the capability of HARPS-N in detecting Earth-like exoplanets [119].

A partially-stabilized 1-GHz Ti:sapphire laser was used by McCracken *et al.* [13] as the source comb for calibrating the High Resolution Spectrograph (HRS) on the Southern African Large Telescope (SALT). The Ti:sapphire comb was repetition-rate stabilized, with f_{CEO} monitored by heterodyning the comb against a narrow linewidth diode laser stabilized to a hyperfine Rb transition. The offset frequency shifted by less than 2% (20 MHz) over an 8-hour observation window, and could be accounted for in the calibration process. The Ti:sapphire laser was spectrally broadened in a short length of PCF and the modes filtered in a tunable Fabry-Pérot etalon, offering 15-25 GHz spacing over 550–890 nm, fully covering the red arm of the spectrograph. Comb calibration improved the wavelength solution by a factor of two and established a higher resolving power for the high stability mode of HRS than was previously assumed.

3.3 Electro-optically modulated lasers

An EOM comb constructed entirely from commercial off-the-shelf components was deployed by Yi *et al.* [96] at the NASA Infrared Telescope Facility (IRTF) and the W. M. Keck observatory (Keck) 10-m telescope, with campaigns in 2014 and 2015 respectively. A narrow-line CW laser was stabilized to a pressure-broadened transition in hydrogen cyanide at 1559.9 nm. Out-of-loop measurements showed a stability of <60 cm s^{-1} for averaging times greater than 20 s, and a frequency drift of <1.2 cm s^{-1} per day, suitable for short-term measurements but implying that further investigations would be required for multi-year campaigns. The CW laser was modulated in both phase and amplitude using a series of $LiNbO_3$ modulators before being amplified, resulting in a 1-W, 12-GHz, 2-ps pulse train. Broadening from 4 nm to over 100 nm was carried out in 20 m of HNLF. While observation time at IRTF was plagued by bad weather, the campaign at Keck revealed a sub-pixel drift in the comb line positions on the CCD over a period of one hour, directly correlated to temperature drifts within the spectrograph itself.

An EOM comb is being designed for the Subaru Telescope by Kashiwagi *et al.* [120] using a similar pump scheme. By modeling a series of cascaded HNLFs with carefully selected zero-dispersion wavelengths a 12.5-GHz comb spanning over 100 THz was achieved. A Fabry-Pérot etalon was employed prior to amplification and broadening to remove unwanted ASE, resulting in high contrast comb lines.

In a complementary approach, Chavez Boggio *et al.* [121,122] demonstrated a novel astrocomb generated from two amplified narrow linewidth CW lasers near 1550nm that were co-launched into 1.5 m of low dispersion HNLF. Four-wave mixing products resulted in a 60-THz comb centered at 1600 nm which was subsequently frequency doubled in BBO to produce a comb at 800 nm with a modal separation of 708.5 GHz. While in its early stages, this work is promising for the generation of extremely-widely-spaced astrocombs.

4. Outlook

In this article we have highlighted the advances made in the development of frequency combs for astronomical spectrograph calibration. With metallic cathode Th-Ar lamps no longer available on the market [9], astrocombs may soon be considered the primary source for spectrograph calibration rather than a luxury, and their performance must improve to meet this challenge accordingly.

4.1 Challenges

While nonlinear optics enables the broadening of a relatively narrow source comb, many practical astrocombs provide far narrower wavelength coverage than the spectrograph upon which they are deployed. The limiting factors lie in the inherent trade off between sideband suppression and operational bandwidth of the Fabry-Pérot etalons required for mode filtering, requiring multiple etalons to cover different spectral regions. The proposed spectrograph for the E-ELT will require a calibration source that covers 0.37–2.1 μm and an operational lifetime of 10 years – no astrocomb to date has demonstrated this requirement [72]. An alternative technology may be Fabry-Pérot etalons illuminated by a broadband white-light source, producing a comb-like structure. Fixed etalons have been employed as calibration sources demonstrating ~1-m s^{-1} stability demonstrated over several months [123], with primary challenges including vacuum and temperature stabilization and dispersion drifts. Tunable etalons must be stabilized to an optical reference such as an atomically stabilized diode laser or a laser frequency comb. Such stabilization can enable few-cm s^{-1} accuracy [124–126], however the use of a reference places additional demands on the engineering of the etalon coatings.

Full automation remains a technical challenge. The astrocomb at HARPS-N has been upgraded to include auto-alignment of the flat-mirror Fabry-Pérot etalons and coupling into the tapered PCF. Care must still be taken to ensure that contaminants do not damage sensitive components, particularly in fiber systems with high average powers. Ti:sapphire systems require periodic adjustment of the crystal position to prevent damage from the optical tweezing of dust, which alters f_{CEO}. This can be compensated for using motorized intracavity wedges, however this is currently a manual process. The recent upgrade to the astrocomb at HARPS includes a significant redesign to aid automation, with studies of long-term fail-safe operation underway [79].

Within the astronomy community, questions remain over whether astrocombs are truly required to achieve the greatest radial velocity precision from a spectrograph. Lovis *et al.* performed an in-depth study of Th-Ar lamp spectra at the HARPS spectrograph, estimating a global uncertainty in the wavelength calibration of 0.2–0.4 m s^{-1} in observations taken over a 1-month window [7]. A comparison of the spectra from different Th-Ar lamps taken during the same night revealed 1 m s^{-1} line shifts, which may have been attributable to instrument drifts or CCD limitations rather than calibration standard variation. In short, astronomers have had many decades of experience working with Th-Ar lamps, reducing the calibration uncertainty to near-cm-s^{-1} level, and thus far the performance issues and technological difficulties associated with astrocombs have not yielded the promised benefits or results.

While sub-cm-s^{-1} wavelength calibration may be soon be achievable with an astrocomb, the choice of calibration source is not the limiting factor in the radial velocity precision achievable with a high-resolution spectrograph. Technological issues include photon noise [127], guiding and modal noise associated with optical fibers [128], and CCD stitching errors [10], although these can all be addressed with a sufficiently stable instrument. Stellar phenomena such as sunspots, meridional flows, p-mode oscillations and jitter must be accounted for and, where possible, averaged out in order to keep the RV precision below 1 m s^{-1} [129]. Going forward, the astrophotonics community must continue to develop calibration tools that ensure that the wavelength solution is an order of magnitude more precise than other sources of uncertainty, removing this factor from the overall error budget.

4.2 Opportunities

The continual progression of laser technology is opening up new avenues of exploitation within astronomy. The relative expense of a frequency comb makes it affordable by only the largest facilities, however small and medium scale spectrographs would also benefit from comb calibration. Where multiple telescopes are located in one geographical location a single frequency comb could be distributed from a central hub via low-loss single mode fiber, and the structure of the comb can be preserved over multiple km [130].

New and emerging laser sources will find applications as astrocombs in the future, particularly the microresonators and compact solid-state lasers previously mentioned. The wide mode spacing offered by these systems would also enable direct optical frequency stabilization to an atomic reference through saturated absorption spectroscopy [131], providing intrinsic atomic traceability for each comb line without an additional CW laser.

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Astrocombs may have a role in the pre-calibration and validation of lower cost calibration technologies such as white-light etalons [132].

As spectral flattening improves there is an opportunity to use the astrocomb not only as a precision wavelength calibrator, but also as an ideal white light source for flat-fielding of the CCD. Tungsten filaments are currently employed for this purpose and flat-fielding is carried out daily, however the filaments age over time and therefore suffer from intensity variations. They are also subject to the same manufacturing limitations as hollow cathode lamps, making it difficult to compare data sets. The intensity profile of a filament is not constant with wavelength, introducing signal-to-noise errors in the flat-field calibration. With photon-flux-per-few-comb-lines shaping possible [133], the comb could be used for this purpose, providing identical, traceable flat-fielding.

Compact laboratory spectrographs constructed from commercial off-the-shelf components for the analysis of astrocombs have recently been reported [134,135]. While they lack the environmental stability of large-scale systems, their comparative resolving power of $R >$ 150,000 enables the analysis of sideband suppression and other systematics.

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